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Clay minerals and their implications for Late Quaternary palaeoclimate investigation: A case study in Pontian, Johor

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Abstract: Paleoclimate during Quaternary can be inferred from clay minerals composition in the coastal deposit acquired from the west coast of Johor, wherein this particular region has been linked with the few scholarly efforts delineating the field. This present study examined several core materials sourced from Pontian, Johor, mainly due to their almost entirely fine-grained sedimentary sequence suitable for high-resolution clay mineral assessment. Accordingly, semi-quantitative clay minerals assemblages were obtained by employing a series of measurement repetitions of air-drying, glycolation, and heating up to 350 °C and 550 °C on the sample conditions via X-ray diffraction (XRD) method. These assemblages were found to be predominantly kaolinite and illite in nature, apart from the presence of minor chlorite and smectite possibly sourced from the tuffaceous deep water deposit and granitic intrusive rock in central Johor. In line with this, stratigraphic clay mineral records revealed that the Late Quaternary experienced climatic changes between warm and humid conditions, whereas drier conditions were correlated to Greenlandian and Northgrippian sub-epoch of Holocene.

Keywords: Clay minerals, Holocene, paleoclimate, Quaternary, stratigraphy

Abstrak: Iklim kuno Kuaterner boleh dikenalpasti melalui komposisi mineral lempung yang didapati dalam enapan pesisir pantai barat Johor, di mana bidang ini kurang diketengahkan secara akademik di rantau ini. Kajian ini melibatkan teras gerudi dari Pontian, Johor yang hampir keseluruhannya berbutiran halus di mana cirian ini amat sesuai untuk penilaian mineral lempung beresolusi tinggi. Himpunan mineral lempung separa kuantitatif telah diperoleh melalui teknik pembelauan sinar-X. Sampel-sampel berkenaan diukur secara ulangan dengan syarat tertentu iaitu keringan udara, pengglikolan, pemanasan sehingga 350 °C dan 550 °C. Himpunan-himpunan lempung berkenaan didominasi oleh kaolinit dan illit serta sedikit komponen klorit dan smektit berkemungkinan berasal dari enapan laut dalam bertuf dan batuan granit terobosan dalam di kawasan pertengahan Johor. Maka, rekod stratigrafi mineral lempung ini menunjukkan perubahan iklim panas dan lembap kepada iklim yang lebih kering di Kuaterner Akhir. Ini boleh dikorelasikan kepada epok Greenlandian dan Northgrippian dalam Holosen.

Kata kunci: Mineral lempung, Holosen, iklim kuno, Kuaterner, stratigrafi

INTRODUCTION

Clay minerals analysis is a useful tool for paleoclimate recognition (Deocampo & Jones, 2013) mainly because their formation is rooted in the weathering processes that occur throughout periods of geological succession. In essence, it reflects the extent of weathering or hydrolysis that happens in land masses located adjacent to sedimentary basin. Sedimentary processes are generally linked with alterations of deposited materials due to varying reasons, including sedimentary structure, climate variation, and depositional environment. For example, marine, lacustrine, and fluvial environments that interact with detrital minerals and water lead to the formation of in situ mineral facies (Boggs, 2014). Clay minerals, in particular, are also subjected to such alterations and correlated with Earth processes typically identified near the surface of the Earth, a characteristic attributable to thermodynamic stability required during their formation and phase changes (Weaver & Pollard, 1973; Meunier, 2005; Deocampo, 2015).

Accordingly, coastal deposits seen along the west coast of Peninsular Malaysia are important localities in Quaternary studies (Suntharalingam, 1983a; Lee *et al.*, 2004). The stratigraphy found within these beds occurs due to sedimentary processes and reflects possibly sensitive markers of environmental shifts and differences, thereby associated with climate change variability and identification (Kamaludin, 1993; Azmi & Kamaludin, 1997). Throughout time, such proxies are predominantly biotic in nature, depicting palynological traces and other biological remnants (Kamaludin, 2002; Tjia & Sharifah Mastura, 2013; Minhat *et al.*, 2016). Meanwhile, certain cases may not contain proxies for paleontological evidence due to the prevailing environmental conditions or

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taphonomic factors, thus rendering indicators that do not require preserved biota usage as critical.

Batchelor (2015) reported the insufficiency of dependency on sedimentological evidence in Quaternary sediments alone to interpret possible environmental conditions. This is ascribed to the finer Quaternary sediments along the western coast of Peninsular Malaysia due to low gradient slope and tidal-influenced processes. Therefore, the limited vertical variation in grain size in the sediments, which ranges from silt to clay with occasional coarse sand, enables the differentiation of clay mineral proxy that is more susceptible to the environment and climatic processes from other proxies as reflected by various clay mineral species alterations. Consequently, information obtained from these clay minerals reflects the mixture of temperature and precipitation effects, while detrital clay minerals are implementable as tracers for different purposes, such as sediment transport processes, dispersal, and provenance.

Clay minerals found in Quaternary sediments sampled from Pontian, Johor offer in-depth knowledge regarding paleoclimate and paleoenvironment for the area as a result of their direct formation via weathering or hydrolysis process. In particular, they are produced from the parent minerals of feldspars and micas in sedimentary rocks with widespread tuff and acidic intrusive; both in central Johor. Therefore, the main objective of this present study is to depict the climate relationships that influence clay minerals composition passed on the samples obtained from Quaternary sediments on the west coast of Johor. Reconstructing the paleoclimatic and paleoenvironmental shifts observed during the Late Quaternary in western Johor was achieved by examining the relative amount of disparate clay minerals via XRD method.

GEOLOGICAL SETTING

Quaternary deposit typically occurs as a fluvio-estuarine along the west coast of Johor (see Figure 1). Deposition is continually observed to the southern direction of Sungai Pulai, signifying a transitional depositional environment that can be depicted by siliciclastic sedimentation, high terrigenous input, and significant marine influence. Sediment provenance, including clay minerals, is likely to originate from Triassic sedimentary rocks (Gemas Formation) and Permian-Triassic granite intrusive at central Johor.

The study location is situated in the middle section of Sungai Pulai, which is proximal to terrigenous and marginal marine processes, such as fluvial and tidal influences. The core obtained exhibits fine-grained deposits and is estimated to encompass Late Quaternary sequence; however, burial conditions are dismissed due to its young geological age. Besides, late Pleistocene interglacial transition is associated with ice sheet melting at higher latitudes (Paillard, 2001; Walker *et al.*, 2018), thus leading to global sea-level rise that causes significant landscape changes in Sundaland (Sathiamurthy & Voris, 2006; Hanebuth *et al.*, 2011) and denoting the most affected coastal areas. Such relative sea-level increment within the Late Quaternary (Holocene) period is a topic highly discussed among many scholars (see Geyh *et al.*, 1979; Kamaludin, 2002). Therefore, further data were gathered to identify local geological changes from clay mineral assemblage records.

Previous Quaternary clay mineral studies

The scarcity in Quaternary deposits literature in the context of Malaysia reflects the scarcity of studies pertaining to clay deposits. One of the earliest studies conducted by Shamsuddin (1984; 1986) revealed kaolinite as a predominantly large fraction of clay composition in Quaternary deposit for Peninsular Malaysia that was distinguished in terms of weathering degree. Similarly, Raj (1987; 1993a) reported the clay properties from different parent rocks, in which interstratified clay minerals are commonly encountered in partially weathered samples,

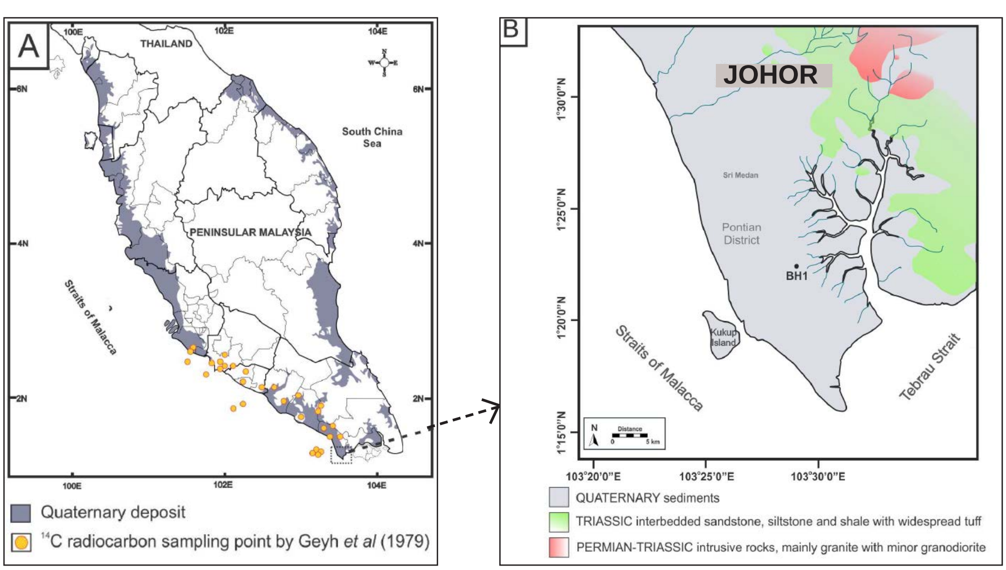

Figure 1: (A) Sampling locations of radiocarbon age study by Geyh *et al.* (1979) in Peninsular Malaysia with Quaternary deposit in grey. (B) Location of BH1 and distribution of Mesozoic sediments of Gemas Formation and acidic intrusive (modified from a map published by the Director-General of Minerals and Geoscience Malaysia, 2012).

followed by a notably increased kaolinite and decreased illite in those subjected to more weathering. Meanwhile, a low-resolution study by Raj (1990) carried out in west Johor is the first to observe the prevailing montmorillonite concentration in the upper part of Holocene sediment, while other authors have highlighted kaolinite and illite as the dominant components in Quaternary sediment found in Perak (Suntharalingam & Teoh, 1985; Suntharalingam, 1987). While the end-product of clay varies according to its provenance, clay mineralogy is largely influenced by sedimentary environment (Anizan, 1992).

MATERIALS AND METHODS

BH1 was drilled in Pontian District, located in the western coast of Johor, Malaysia (GPS Coordinate: 1’ 22” N, 103’ 29” W), where a 42 m sequence of Quaternary sediments was successfully recovered. The sediments consisted of silt, silty clay, and peat deposit with various colours ranging from white to grey and brown to light orange (see Figure 2). Here, humic and calcareous materials were commonly encountered throughout the sequence, while several intervals were significantly enriched with these contents.

Next, 40 samples were selected at 1 m interval for clay mineral assemblage purposes using XRD. Accordingly, each sample was subjected to disaggregation by using an agate mortar and pestle, following which an ultrasonic bath was implemented to further disperse them. After that, extraction of clay with a size fraction of < 4 µm spherical diameter was performed from the upper 5 cm of the suspension, following its settling for 3 hr and 10 min per Stoke’s Law. This was followed by the preparation of oriented sample smears on glass slides based on a technique prescribed by Moore & Reynolds (1997).

The next step entailed XRD data collection on a Rigaku Miniflex 600 diffractometer, which was operated at 40 kV and 15 mA, and embedded with a copper anode (Cu-Kα radiation). Accordingly, the clay samples were subjected to scanning that spanned from 2° to 70° 2θ, with 0.02° step size at 1.5°/min scan speed. As a result, four XRD patterns were obtained from every oriented sample smear using the techniques described in Carroll (1970). The first pattern was generated from a slide subjected to air-drying only. Next, it was placed in a desiccator loaded with ethylene glycol for 1 h at 60 °C to yield the second XRD pattern. Meanwhile, the third and fourth XRD patterns were successfully isolated after subjecting the sample to heat treatment at 350 °C and 550 °C for 4 and 6 h, respectively.

Scanning electron microscopy (SEM) was performed using a Hitachi SU1510 Scanning Electron Microscope attached to an Oxford detector of energy dispersive X-ray (EDX) to determine the chemical composition of each element or compound in the samples. The samples for SEM-EDX analyses comprised of typical clay-dominated bulks. The freshly broken surfaces of the four samples were cohered

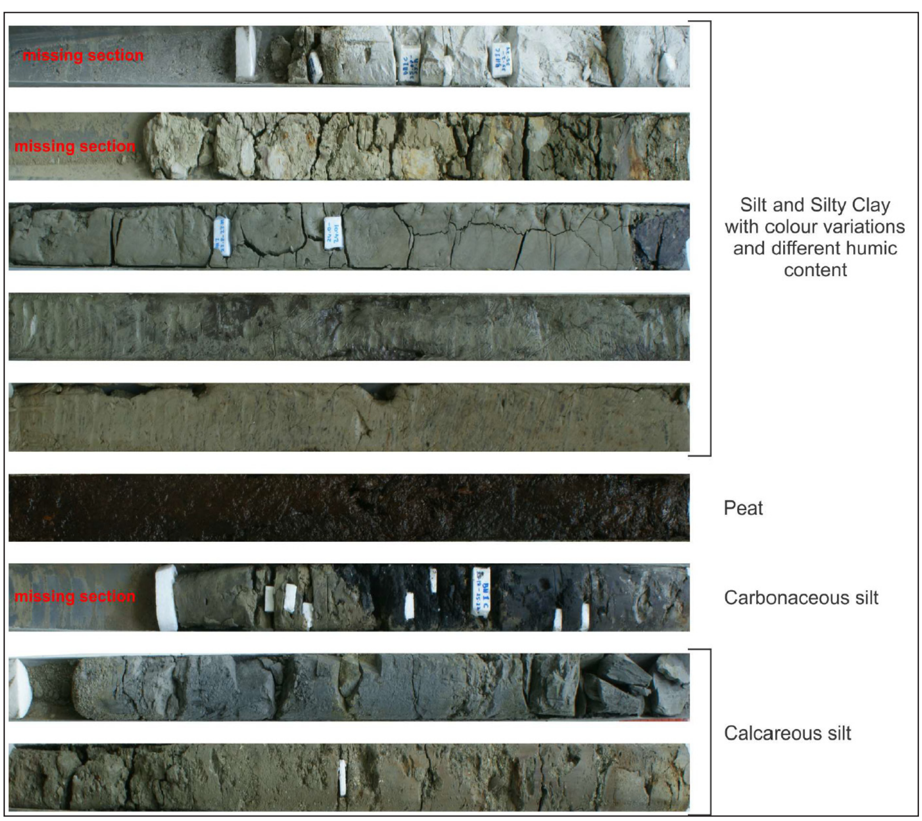

Figure 2: The lithology profile of BH1.

onto an aluminium sample holder with duplex-sided tape and thin-gold coated using a Hitachi E1010 sputter coater. Single-point EDX quantifications were attained using the same SEM capture point.

RESULTS

Clay mineralogy

Figure 3 illustrates kaolinite and illite as the clay minerals mostly found in the samples. Smectite and 10-14 Å clays were found to be highly widespread, whereas mixed illite-smectite (I-S) layer clays were absent in all samples. All the four clay mineral assemblages were distinguished based on the relative proportions of kaolinite, illite, chlorite, and smectite. For example, glycol saturation resulted in smectite mineral structure expansion, thus separating it from chlorite (001) peak.

Most of the glycol-saturated samples displayed peak shift due to the aforementioned smectite expansion, while concurrently revealing resolvable chlorite (001) peaks and peaks obtained due to kaolinite (001) reflections (see Figure 4A). Meanwhile, heating the samples to 350 °C for 4 h led to a complete collapse of smectite expandable spacing,

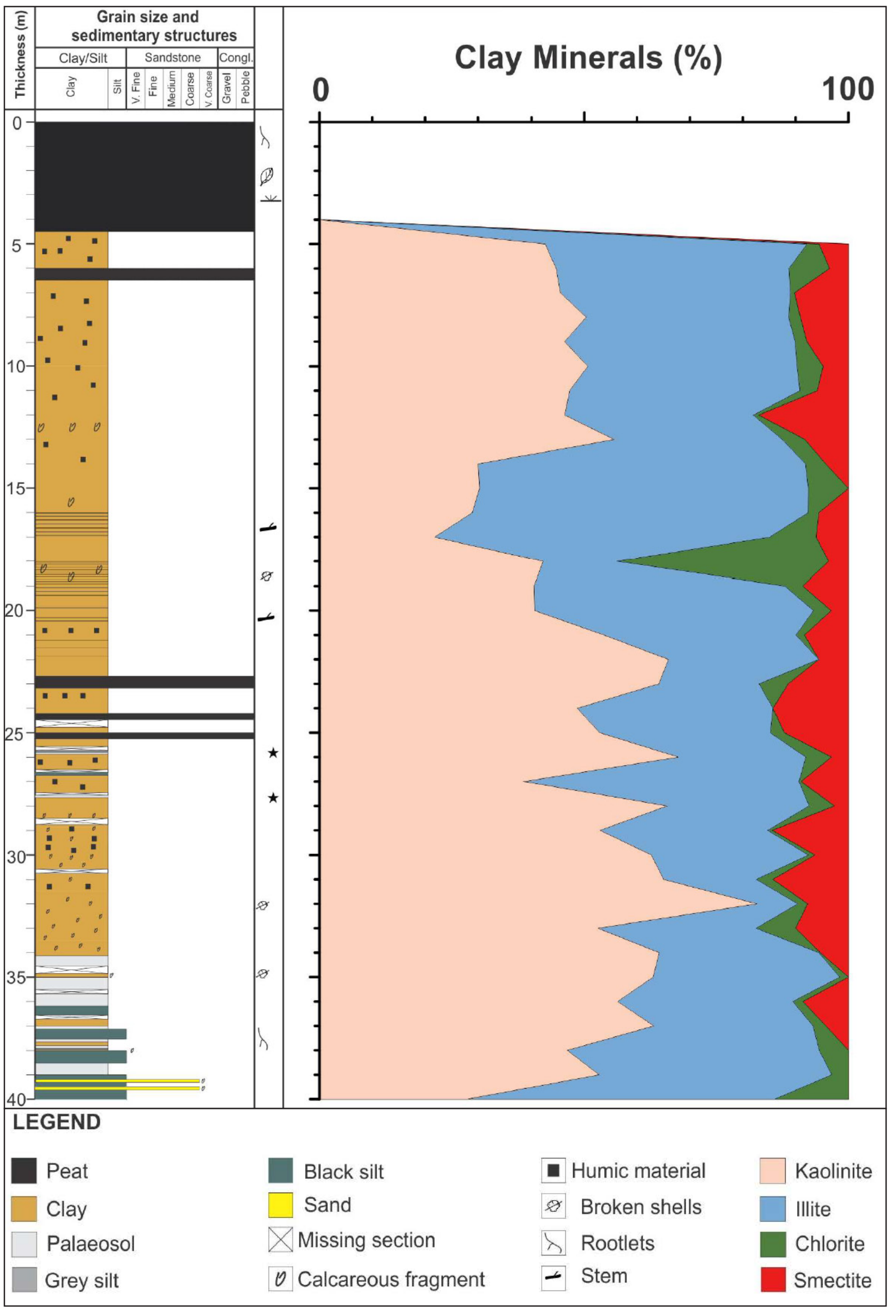

Figure 3: Downhole distribution of clay minerals for BH1 samples from a proportion of < 4 μm fraction.

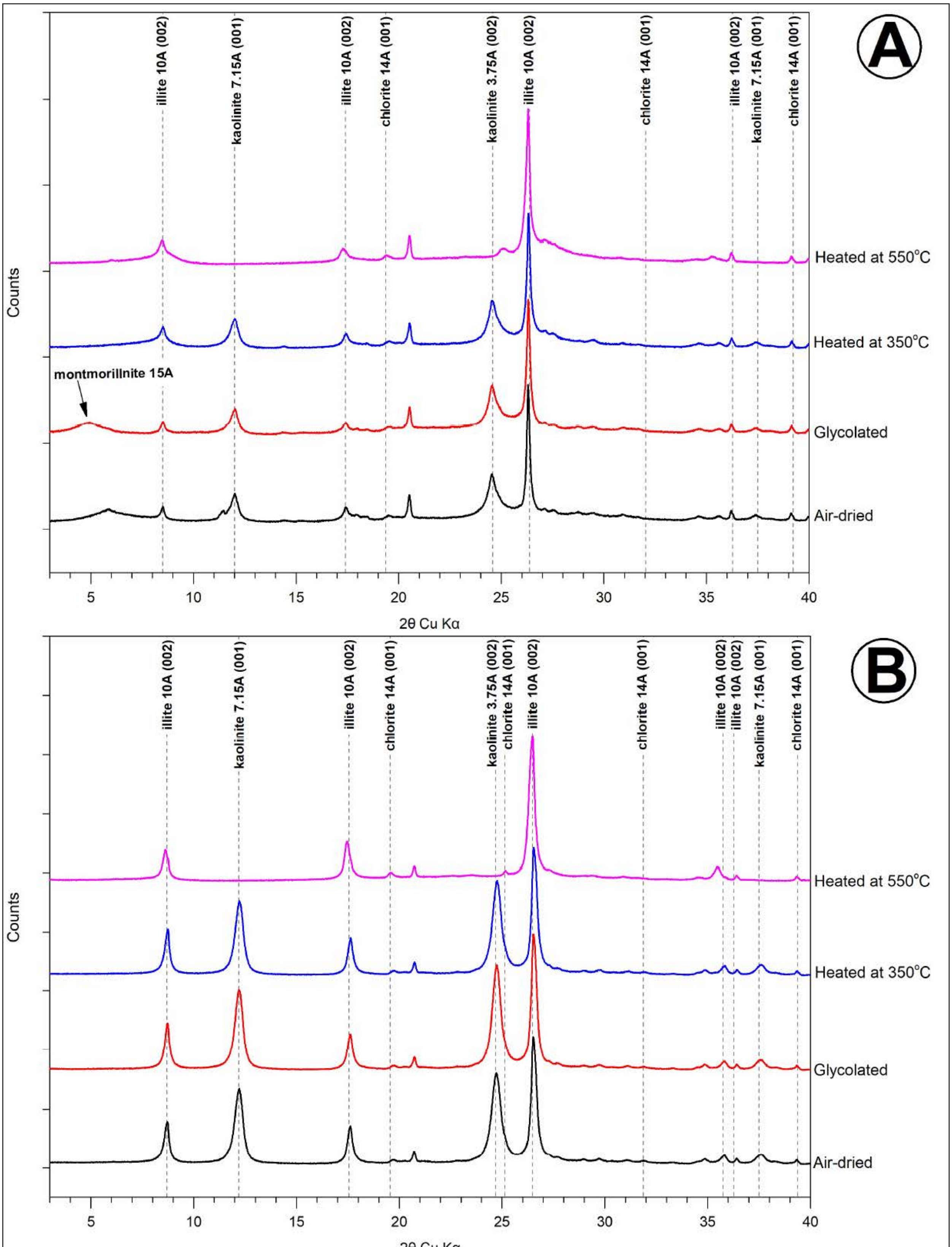

Figure 4: Sample XRD traces (air-dried, glycolated, and heated at 350 °C and 550 °C) to identify clay mineral assemblages in west Johor samples: BH1 clay fractions at (A) 7 m and (B) 39 m.

thus confirming the existence of mixed I-S layers. Chlorite fractions, which were ascertained using the measured values of undifferentiated chlorite + kaolinite, was identified by determining if their peaks were present after repeating the scans. This is carried out after the samples were subjected to heat at 550 °C, which rendered kaolinite amorphous while chlorite persisted in an intact condition (see Figure 4B).

Clay mineral assemblages for samples sourced from the upper and base parts of BH1 were found to be predominantly kaolinite and illite in nature, with minor chlorite and smectite contents along with absent traces of mixed I-S layers (see Figures 4A and 4B). Here, chlorite and smectite clays were generally detected in variable proportions towards the top of the core.

Clay mineral indicator

Environmental changes may be predicted in clay mineralogical analyses by using the ratios of clay minerals, such as kaolinite/smectite (K/S) and kaolinite/illite (K/I), as useful indicators (see Thiry, 2000; Liu *et al.*, 2020). Relative variations of clay minerals content are more reliable in reconstructing paleoclimate than using absolute values to differentiate parent materials (Chamley, 1989). However, various data interpretations of clay mineral ratios have been applied, including K/S ratio to compare glycolated peaks (Bolle & Adatte, 2001) and subtraction of background peak height for each type of clay minerals (John *et al.*, 2012). In this study, semi-quantitative values and ratios of clay mineral data were analysed to predict the paleoclimate trends.

Morphology of clay minerals

Figure 5 displays the qualitative comparison between SEM morphology and XRD analyses for illite, smectite, and kaolinite. Figure 5A shows an unusual illite clay type of 45 µm length with tiny laths and fibrous texture; indicating authigenic mineralisation that might aggregate with filamentous and platy morphology (Wilson *et al.*, 2014). The occurrence of fibrous illite is linked with the acidic anions of organic oxalates, which are commonly found in plants (Small & Manning, 1993). Additionally, the EDX analysis revealed traces of K, Fe, and Mg, which are common in illite.

Figure 5B portrays the crystal of smectite with interwoven arrangement and wavy pattern. The EDX analysis identified Fe, Mg, K, Ca, and Na as trace elements, which are consistent with smectite but not with illite or chlorite. In general, Al-rich smectites are derived from mica-schist; Mg- and Fe-rich smectites come from the subvolcanic sediment (Drief & Nieto, 2000). Hence, Al, Ti, Fe, and Mg in clay minerals suggest that these minerals most likely derived from biotite (Villaseca & Barbero, 1994).

Figures 5C and 5D display kaolinite in platy and booklet forms in ample amount with plates ranging from 5-20 µm in diameter and booklets from 2-5 µm in length. The EDX examination revealed high peaks of silicon and aluminium, which signified the presence of kaolinite clay. In a similar vein, SEM evaluations unravelled the fact that kaolinite contained almost pure $Al_4Si_4O_{10}(OH)_8$. In general, kaolinite crystals were found either in cleaved, books of plates or platy form (Psyrillos *et al.*, 1999). The platy and booklet kaolinite discovered in this study is ascribed to a direct replacement of altered minerals. For instance, blocky kaolinite crystals were altered authigenically from precursor minerals, notably from feldspar, muscovite or chlorite, whereas platy kaolinite crystals might have detrital origin.

Nonetheless, no chlorite crystal was detected explicitly in the SEM examination. Chlorite crystals may exhibit randomly arranged subhedral plates with size ranging at 3-8 µm and occasional rosette-shaped clusters (Humphreys *et al.*, 1989). Hence, they might texturally resemble kaolinite crystals (see Figures 5C and 5D). As a result, chlorite and kaolinite crystals were indistinguishable. Overall, the SEM analyses exhibited a mixture of authigenic and detrital profiles for both crystal textures and morphologies of clay minerals. This particular observation is in agreement with the local heterogeneity of physical and chemical conditions in tidally-influenced environment.

DISCUSSION

Clay mineral provenance

Distinctly, the kaolinitic nature of Quaternary sedimentary sequence found in west Johor was determined as the end-product of extensive weathering episodes. The material is known as a secondary mineral, otherwise generated via intense chemical weathering subjected to K-feldspar, muscovite, and mica in rocks (Chamley, 1989). Due to its prevalent formation in rapidly leaching landscapes (Pédro, 1989), other clay minerals, such as illite and chlorite, were likely chemically altered *in situ* to kaolinite via tidal reworking as noted in SEM analyses. Therefore, comparably high kaolinite content observed in the deposits is attributable to high degree weathering of intertidal deposits noted throughout the low gradient slopes of west Johor.

On the contrary, illite emerged as a significant clay component observed in BH1 with a small percentage of chlorite. They are denoted as primary minerals among different detrital clay minerals (Weaver, 1989), whereby chlorite is mainly the typical type seen in low-grade metamorphic rocks. Besides, it is a direct product of mafic rocks subjected to weathering despite minimal hydrolysis (Velde & Meunier, 2008). Upstream, potential parent-source rock included igneous rock that contained micaceous minerals (e.g., biotite and muscovite), which were structurally similar to illite. The mudstone associated with turbidite deposits also contained a substantial amount of illite (Loganathan, 1977). Therefore, it is highly probable that both illite and chlorite contents observed are direct products of physical weathering due to acidic intrusive identified in central Johor, on top of the partial weathering from Gemas Formation shale. Chlorite and illite were typically found in immature

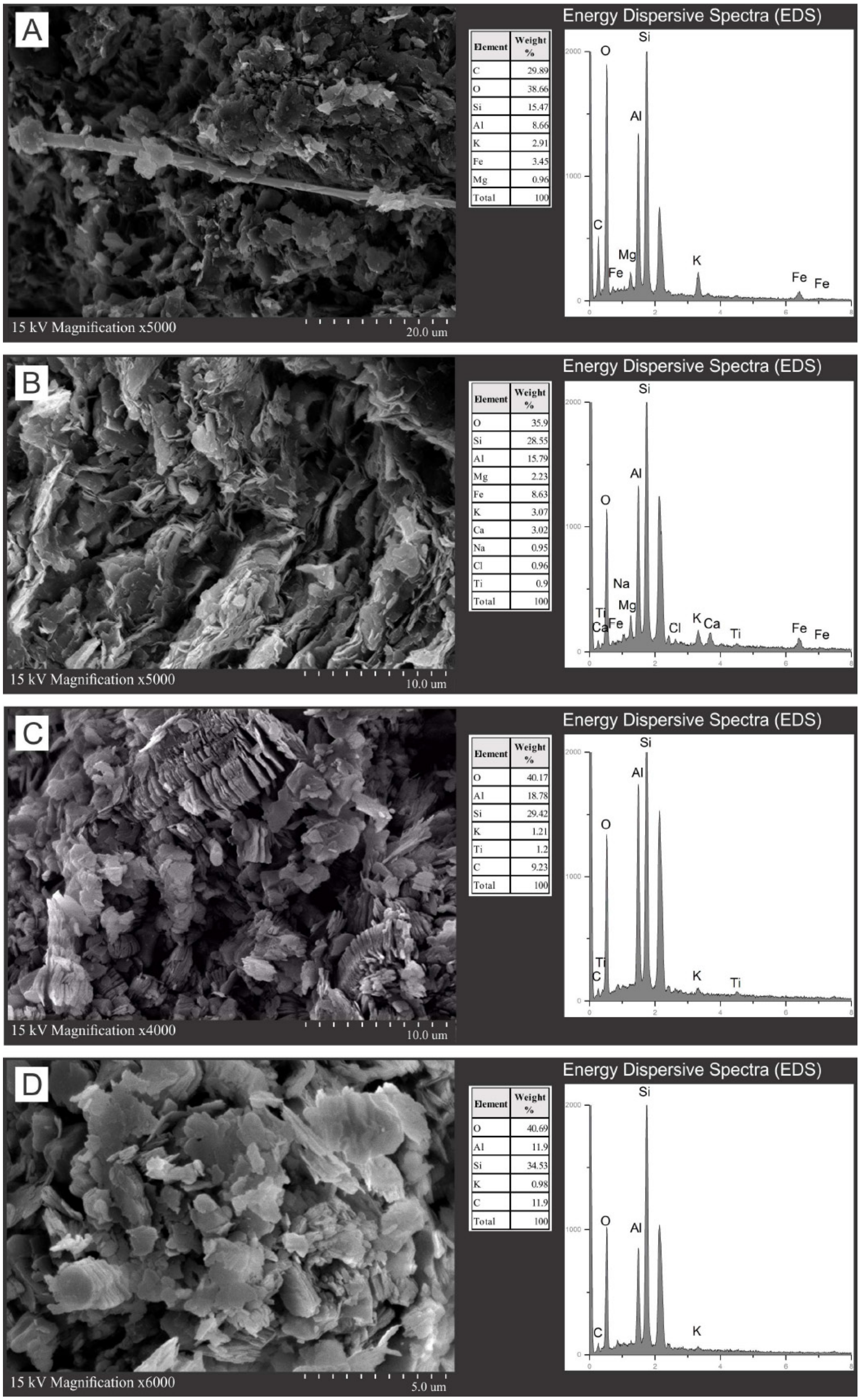

Figure 5: SEM images: (A) Illite in fibrous form and small-lath-like crystals, (B) Detrital plate of smectite with undulating microstructures, (C) Authigenic kaolinite forming stacks of subhedral to euhedral pseudohexagonal platelets, and (D) Flaky habit of subhedral kaolinite crystals.

soils at early stages of weathering with comparatively faint chemical petrifying, which mostly occur across drier and colder pedoclimates (Hong *et al*., 2007).

The smectite content evidenced the presence of predominant volcaniclastic components in the sediments, in which volcanic material was noted from tuff interbedded with sandstone, siltstone, and shale Triassic deposits from the Gemas Formation in central Johor. This is because; smectite is a secondary mineral produced either via volcanic material alteration or transformation procedure that happens in the soil due to recombination. In particular, recombination of cations produced from parent aluminosilicate and ferromagnesian silicate occurs in warm and humid environments within a confined area in the catchment (Chamley, 1989). To this end, smectite concentration or smectite/illite (S/I) ratio is commonly applied as a proxy of chemical weathering rate in watershed. Typically denoted as an output of pedo-genetic weathering, smectite abundance is a sign of warm and wet climate conditions (Chamley, 1989; Weaver, 1989).

Presumably, tuffaceous parent rock produces the smectite portion prior to weathering and transportation. The probability of a dissimilar source for illite and chlorite components found in fine-grained deposits is also underlined, which is also detrital in nature. In light of soil development, kaolinite is commonly found in humid and tropical climates (Bergaya *et al*., 2006; Dianto *et al*., 2019). Its formation is significant across the profiles following high rainfall volume throughout a year in distribution, thus generating clay-dominated deposit across low gradient coastal plain.

Paleoclimate and estimated timeframe

In general, clay minerals assemblages can be influenced by multiple attributes, including climate, time, parent material, topography, soil profile type, transport processes, and burial diagenesis (Singer, 1984; Hillier, 1995). Accordingly, the paleoclimate information present in BH1 borehole is possibly conserved and represents a wide intertidal area, which is proximal to landmasses and has yet to be subjected to burial.

In present day setting, the continental soil authigenesis of precursor smectite denotes the presence of alternating tropical climates (warm and humid), especially a drier climate during Late Quaternary. Accordingly, the time window was estimated by correlating the adjusted core position relative to the mean sea-level using carbon-14 dating data retrieved from Geyh *et al.* (1979) on the west coast of Peninsular Malaysia. The present BH1 depositional pattern displayed notable similarities and consistencies with other previous Quaternary studies (see Tjia *et al.*, 1977; Gray *et al*., 1978). The peat sequence turns into a stratigraphic marker when the relative sea-levels show slight variation, as constrained by the radiocarbon age due to principally slow peat accumulation (Dommain *et al*., 2011). Nevertheless, this correlation might have some uncertainties due to the vertical variation depicted by different stratigraphic thicknesses and depositional profiles (Ainsworth, 2005). To this end, the stratigraphic compositional patterns showcase remarkable clay assemblages trends via cored succession, thus detecting the climatic shifts observed at vertical variability despite the complex interaction of multiple factors that control the process (see Figure 6).

Zone 1 (Interval 40 - 28 m). Zone 1 could be correlated to a sediment interval ranging from -33.65 to -33.75 m and from -21.10 to -21.20 m (Geyh *et al.*, 1979), indicating 10,590 - 8,490 BP radiocarbon age. Increased kaolinite content in mudstone sequences (higher K/S) reflects climate changes to warm and humid conditions, as well as intensified chemical leaching alike (see Bolle & Adatte, 2001; Chen *et al*., 2016). Therefore, the low ratio of kaolinite to illite-smectite (K/(I-S)) and K/I values recorded in this present work signify warm and humid climate, thus generating more smectite and illite clay mineral assemblages, as well as increased kaolinite concentration. Meanwhile, unexpected increment and notable deflection in both K/(I-S) and K/I ratios denote the transition to hot and humid climate.

Zone 2 (Interval 29 - 15 m). Zone 2 could be correlated to a sediment interval ranging from -21.10 to -21.20 m and from -12.65 to -12.85 m (Geyh *et al*., 1979), indicating 8,490 - 7,985 BP radiocarbon age. The kaolinite anomaly detected within this depth is ascribed to enhanced chemical weathering and soil formation, primarily because the environment did not undergo any drastic change as evidenced in peat deposit and thin organic matter laminations. This also signifies higher amount of erosion and fluvial discharge, which poses critical insights for hydrology and sediment transport to the depocentre. Paleoclimate is interpreted as a dry climate.

Zone 3 (Interval 15 - 6 m). Zone 3 could be correlated to a sediment interval ranging from -12.65 to -12.85 m and from -2.55 to -2.90 m (Geyh *et al*., 1979), indicating 7,985 - 7,015 BP radiocarbon age. Higher content of kaolinite and illite found in the margins led to the discovery of higher smectite content in western Johor at 15-6 m depth interval; interpretable as progradation effect. Sedimentologically, stronger terrestrial influence in deposits is marked by increased organic matter, indicating sediment supply increment and erosion as the prevalent attributes in a moderately warm and humid climate condition.

Zone 4 (Interval 6 – 0 m). Zone 4 could be correlated to a sediment interval ranging from -2.55 to -2.90 m and +4.70 to +4.95 m (Geyh *et al.*, 1979), indicating 7,015 – 4,270 BP radiocarbon age. Peat succession is interpreted as a significant decrease in relative sea-level. Accumulation of peat, otherwise termed paludification, develops on top of gently sloping mineral soils, thereby occurring together or after an increasingly terrestrial landscape (Klinger, 1996).

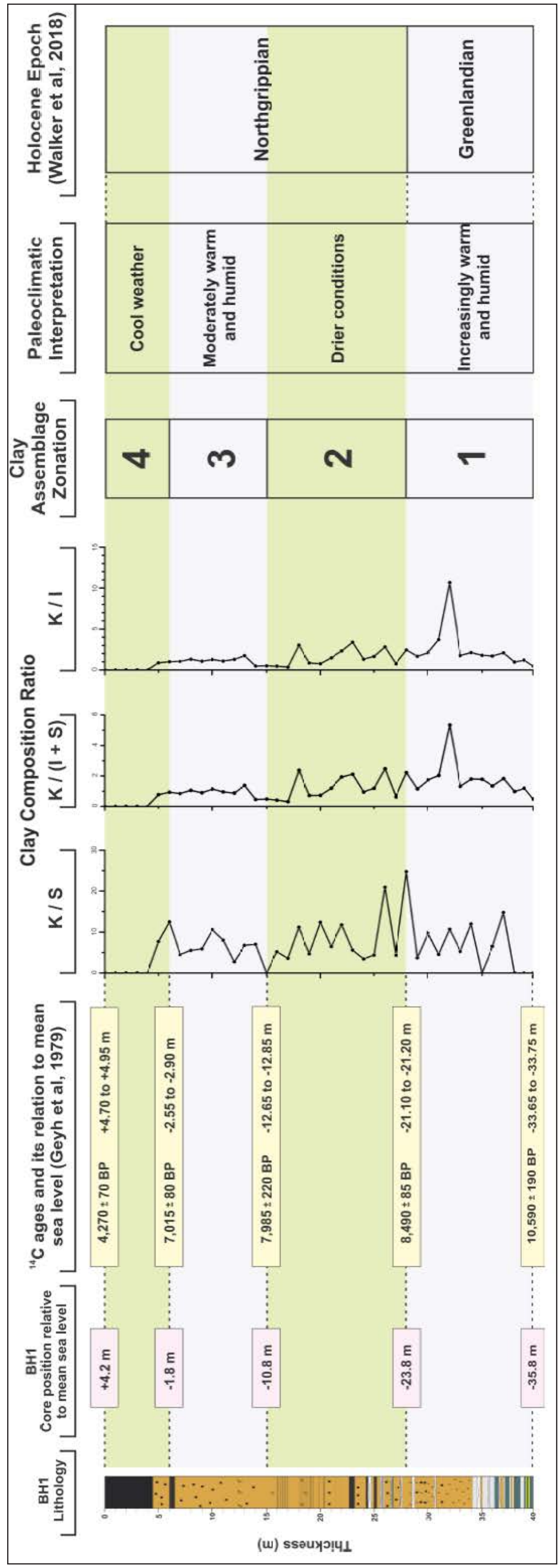

Figure 6: BH1 stratigraphic sediment profile, age window, relevant clay composition ratios, and assemblage zonation determination with climatic interpretations. Correlation was made with subdivisions of Holocene epoch approved by the International Union of Geological Sciences (IUGS) (Walker *et al.*, 2018).

Subdivision of west Johor paleoclimate with formal Holocene epoch

The stability of a long-lasting landscape (> 1 Ma) is the key for forming the equilibrium of mature and thick kaolinite soils, along with the environment (Thiry, 2000); which reflects the later formation of clay composition than the actual deposition. The physical transport processes are chiefly responsible for the subsequent changes in BH1 clay mineral assemblages, particularly in sediments younger than 1 Ma that could have also undergone some secondary mineralogical changes. Besides, highly marked fluctuation for fine sediment input behaving as the suspension load (as evidenced by kaolinite content) is mainly triggered by physical weathering and fluctuating water discharges controlled by climate change.

Zone 1 paleoclimate is correlated with Greenlandian sub-epoch despite the small variance of approximately 200 years in terms of age, which is attributable to delayed landscape response following global sea-level changes. A unique signature is detected at a specific level in Greenland ice cores within this timeframe, thus marking an increasingly warm global climate (Walker *et al.*, 2018) and matching the lower part of BH1 patterns. Therefore, the local abundance of kaolinite is closely linked to increased relative sea-level, which is where rampant chemical leaching (hydrolysis and oxidation) in the form of tidal reworking is most likely to occur within the floodplain. This depicts the migration of shoreline and stronger marine influences during this sub-epoch in west Johor.

On the contrary, Zones 2, 3, and 4 lie within the Northgrippian sub-epoch, which are delineated by a specific climatic cooling signal after a duration marked by the increasing temperature during the Early Holocene (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006). After 8,490 BP, the notable presence of high organic deposits is an implication of the flourishing vegetation activity in the west Johor coastal area. This observation is most likely an outcome of regional landscape stability and general acidification of the floodplain, thus indirectly indicating the reduced horizontal extent of tidal influence, lower tidal reworking, and overall decrease in marine influence. Therefore, one may perceive this as the relatively unchanged or lower sea-levels attributed to a cooler global climate.

Paleoclimate data in comparison with regional sea-level data

The proposed sea-level curves for this region are illustrated in Figure 7. Geyh *et al.* (1979) proposed a curve that displays a smooth sea-level variation with maximum elevation exceeding +5 m from MSL. The later construct of sea-level curves (Tjia & Fuji, 1992; Hesp *et al.*, 1998; Bird *et al.*, 2007) suggests sea-level elevation to be no higher than +4 m from MSL, in addition to the uncertainty range in the plot. Similarly, Bird *et al.* (2007) reported an alternate plot with relatively lower upper limit, whereas Hesp *et al.* (1998) and Tjia & Fuji (1992) described a wider range of alternate plots with higher

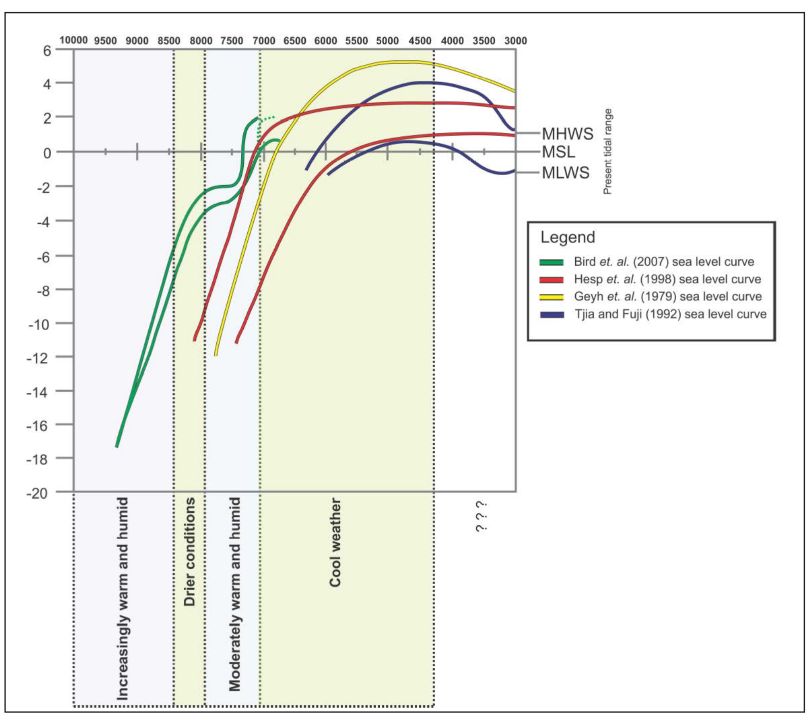

Figure 7: Comparison of the proposed climatic zonation presented in this study and previously proposed sea-level curves for Straits of Malacca and Singapore. The tide reference line is marked for mean high water springs (MHWS), mean sea-level (MSL), and mean low water springs (MLWS).

upper limit. However, the distinct relationship between sampling point and sedimentological processes is omitted in those past studies. By implication, the variance in data distribution is attributed to various localities, whereby both the interaction and the magnitude of depositional processes may differ. Generally, these curves display a significant increase in sea-level from Early Holocene until approximately 7000 BP. Next, the changes in sea-level appeared stagnated or were in a downward trend after ~ 6500 BP. The cause is inevitably linked to multivariate factors, such as climate condition (Törnqvist *et al.*, 2008), glacioisostatic adjustment (Muhs *et al.*, 2012), and terrestrial water storage (Ngo-Duc *et al.*, 2005). Interconnected yet indirect causal factors that affect relative sea-level are difficult to be summarised (Wunsch *et al.,* 2007). Therefore, climate variability inferred in this study may explain this notable difference of rate in sea-level changes. However, the proposed climate zonation may not necessarily correspond to the existing proposed sea-level curves within this region. Whether the proposed climatic zonation can be in reconciliation with Late Quaternary sea-level curves remains unclear.

CONCLUSION

The analysis of clay minerals is effective to reconstruct paleoclimate, in addition to sedimentary provenance that should not be limited to sedimentological profile comparison. Although the process should distinguish varying parameters that affect clay mineral compositions, the resulting variations may sometimes occur in a pattern that can hardly be differentiated from those already recognised thus far. Accordingly, this case study offers a clear-cut analysis of clay minerals composition for Late Quaternary sediments acquired from the coastal plains of west Johor. The subtle impact of global climate on the composition signifies vertical variability in stratigraphic trends. This highlights the efficacy of clay minerals analysis for the purpose of estimating paleoclimatic changes.

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AUTHOR CONTRIBUTIONS

AHH conceptualized the original idea and discussed it with HJ and RO. All authors agreed with the main objective and idea of this paper. Laboratory analysis were performed by AHH. Main section of the manunscript was written by AHH and further elaborated by HJ and RO. Resources and funding were provided by HJ and RO.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content and material of this article.

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